A CLIMATOGRAPHY OF FREEZING RAIN, FREEZING DRIZZLE, AND ICE PELLETS ACROSS NORTH AMERICA

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1. INTRODUCTION

Icing conditions caused by freezing drizzle and freezing rain both at the ground and aloft can significantly impact aircraft performance (Sand et al. 1984; Martner et al. 1992; Bernstein et al. 1999) and aviation operations, such as routing, scheduling, and maintenance. Until recently, however, little research has been conducted to determine the climatological distribution of such icing conditions. Although climatographies of general icing conditions have been created based upon pilot reports (e.g. Kane et al. 1998), a climatography of the actual occurrence of supercooled large droplet (SLD) icing conditions currently is impossible to create because of the lack of widespread, historical measurements of these phenomena throughout the atmosphere. Other weather variables, however, can be used to infer the climatology of SLD icing. According to Bernstein et al. (1997), one weather variable that can be used as an in-flight icing proxy is precipitation type observed at the ground.

In a new study comparing research aircraft encounters and coincident surface observations, Bernstein and McDonough (2000) found that when the aircraft flew in close proximity to surface observations of freezing rain, freezing drizzle, and/or ice pellets (hereafter referred to as freezing precipitation), SLD was often found in the lower atmosphere. Also, after examining 37 cases found between November and March of 1993–1995, Bernstein et al. (1997) found that 48% of moderate-or-greater severity reported by pilots were associated with freezing precipitation. These results are significant since freezing precipitation covered less than 1% of the total area coverage of all icing reports. Clearly, the threat of icing, including SLD is higher in areas where freezing precipitation is reported at the ground than in areas reporting any other type of precipitation, or where no precipitation is reported.

Given the strong association of freezing precipitation reports and in-flight icing, a climatography of freezing precipitation provides a useful indicator of the climatological distribution of icing conditions at low altitudes. Unfortunately, few climatographies of freezing precipitation have been created. The most recent studies include examinations of freezing rain and drizzle across Canada by Stuart and Isaac (1999); an examination of freezing rain across the contiguous US by Robbins and Cortinas (1996); and a study of freezing rain, freezing drizzle, and ice pellets in the US by Bernstein and Brown (1997). While these studies provide some information on the distribution of freezing precipitation, none provide a complete climatological description of all types of freezing precipitation across North America.

The purpose of our study is to create a climatography of freezing precipitation across North America using surface observations. In this paper, we do not attempt to provide provable explanations for the distributions; instead, this paper is meant to serve as a reference for additional climatological research.

2. DATA AND METHODOLOGY

For this study, we used only hourly surface observations from the National Climatic Data Center (NCDC) for the period 1976–1990. This time period was selected because of the data availability at NCDC. We eliminated data prior to 1976 because some station data were only available for one out of every three hours, and we eliminated data after 1990 to assure that present weather observations were taken by human observers and not by the Automated Surface Observing System in the United States.

The surface dataset that we used in this study was created by merging surface data in two different formats (DATSAV2 and TD-3280) into one consistent format. We did not perform additional quality control procedures beyond that performed in the creation of the DATSAV2 and TD-3280 data formats. To ensure reliable statistical results and that the annual cycle was sampled adequately for most years, we only used locations that had at least 80% of the present-weather reports for 10 of the 15 years. Using these criteria, 610 stations across North America were available for analysis.

3. RESULTS

3.1 *Horizontal Distribution*

Across North America, freezing precipitation has been observed throughout most of the US and

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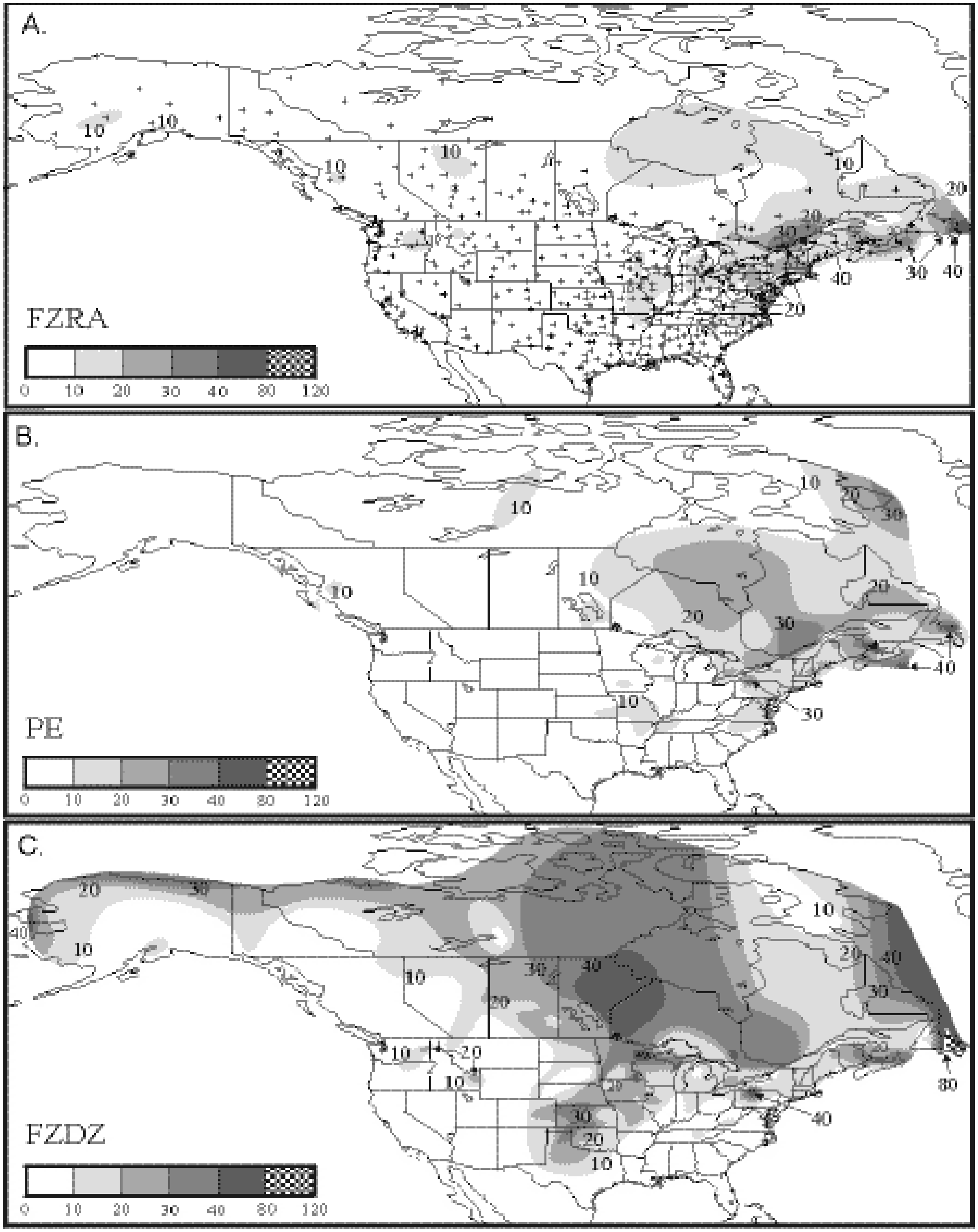

Fig. 1. Expected number of hours of (a) freezing rain, (b) ice pellets, and (c) freezing drizzle annually. Pluses in (a) indicate station locations

Canada. It occurs most frequently across most of central and eastern Canada, north of 32˚N in the central and eastern contiguous United States, and across the northern and western coasts of Alaska. Moreover, this distribution shows synoptic-scale and mesoscale variability (Fig. 1). Of the three types of precipitation we examined in this study, freezing drizzle is the most widespread and occurs the most frequently across the central part of each country and the eastern part of Canada. Ice pellets and freezing rain occur most frequently in the eastern part of each country.

Freezing rain may be considered a significant hazard for low-altitude flights and ground operations because of the potential for rapid ice accumulation. Freezing rain can occur when snowflakes melt as they descend through a deep layer of warm (T > 0˚C) low-level air and remain liquid as they continue to fall through a shallow subfreezing surface layer. This thermodynamic structure produces supercooled water droplets in the lower atmosphere and at the ground that freeze upon contact with subfreezing objects. Freezing rain can also occur as a result of the collision and coalescence process within clouds without a warm layer and a cloudtop temperature greater than -10˚C (Rauber et al. 2000).

Most of North America receives less than 10 hours of freezing rain each year, with the highest frequency near the St. Lawrence River Valley and Newfoundland, where over 40 hours of freezing rain are observed annually (Fig. 1a). These results are similar to Stuart and Isaac (1999), who found in excess of 25 hours of freezing rain annually in several regions across eastern Canada. Based on this distribution and on results of other freezing rain studies (Strapp et al. 1996; Bernstein 2000; Cortinas 2000), we speculate that the maxima occur because of their locations relative to winter-time cyclones, the Atlantic Ocean proximity, and local topographical features, particularly for the St. Lawrence River Valley. The Atlantic Ocean provides a rich source of warm moist air that is advected over subfreezing surface layers, such as those that form in valley locations.

Like freezing rain, ice pellets typically require an elevated warm layer and a subfreezing surface layer. For ice pellet formation, snowflakes either melt partially and refreeze as they descend through the subfreezing layer, or snowflakes that melt completely descend through a deep subfreezing (T ≤ -10˚C) surface layer (Hanesiak and Stewart 1985). The distribution of ice pellets is similar to that of freezing rain. Ice pellets occur most often in the eastern Canadian provinces, where several areas experience more than 30 hours per year (Fig. 1b). In the United States, ice pellets usually occur for > 10 hours annually in the Midwest, the Northeast, and the Mid-Atlantic States.

Some recent studies have shown that freezing drizzle can have a significant effect on aircraft performance (Sand et al. 1984; Ashenden and Marwitz 1997). Most freezing drizzle occurs as a result of collision and coalescence within warm or subfreezing clouds (Strapp et al. 1996; Bernstein 2000; Rauber et al. 2000), with the latter environment present without an observed warm layer in nearly 75%, 53%, and 100% of all freezing drizzle cases reported by Rauber et al. (2000), Strapp et al. (1996) and Jeck (1996) respectively. Freezing drizzle occurs over a large portion of Canada, the central US, and northern Alaska (Fig. 1c), where a maximum annual frequency of greater than 40 hours occurs in eastern Manitoba, western Ontario, eastern Labrador and Newfoundland. Combining all types of freezing precipitation, Newfoundland receives the most freezing precipitation annually in North America. The annual frequency of freezing precipitation in Newfoundland is almost a factor of two over the highest maximum observed anywhere else on the continent.

The freezing drizzle distribution covers the largest area of North America and, therefore, may be the most likely type of freezing precipitation that aircraft will experience annually. The distribution of freezing drizzle suggests that two factors may contribute to its formation: water source proximity and topography. Several studies have found a strong association with the occurrence of freezing precipitation and onshore flow (Strapp et al. 1996; Stuart and Isaac 1999; Bernstein 2000; Cortinas 2000). These studies noted that a large portion of all freezing drizzle events near bodies of water were associated with onshore flow. Bernstein (2000) also found freezing drizzle was associated with upslope flow in the lee of the Rockies and in valleys where stagnant cold air pools and prolonged fog was reported.

3.2 *Temporal Distribution*

For most of the continent, freezing precipitation occurs most frequently during the winter months, except in the extreme northern portions where it occurs throughout the year (Fig. 2). The month of maximum occurrence for freezing rain and ice pellets is January, whereas freezing drizzle occurs

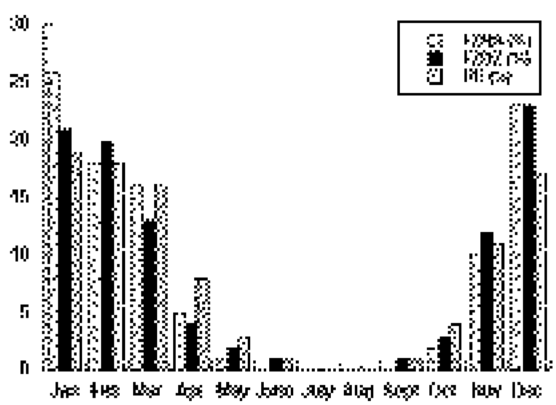

Fig. 2. Frequency (%) of different types of freezing precipitation by month, where FZRA = freezing rain, FZDZ = freezing drizzle, and PE = ice pellets.

most frequently in December. In the fall, there is a rapid increase in the frequency of freezing precipitation between October and December and a similar decrease between March and April. Although freezing precipitation is rare across most of North America during the summer months, it still occurs at far northern sties, such as Barrow, Alaska. Other studies have found a similar monthly distribution for freezing rain in the US (Robbins and Cortinas 1996; Cortinas 2000). These studies also showed that the monthly frequencies can vary significantly among stations and years.

Our preliminary examination of the surface observations indicated that there is an association between the occurrence of freezing precipitation and the diurnal solar cycle. We investigate this possible relationship by using the local sunrise and sunset times for each site to normalize the observation times [hereafter referred to as normalized solar time (NST)]. This normalization sets the sunrise time to 12 UTC and the sunset time to 00 UTC, and divides the hours of daylight and night between 12 NST hours of sunlight and 12 NST hours of darkness. The details of this calculation are discussed by Kelly et al. (1985), who performed a similar analysis for severe thunderstorms. The purpose of this normalization is to identify any relationship between the diurnal solar cycle and the occurrence of freezing precipitation. (In this analysis, we only considered stations located south of the Arctic Circle since north of the Arctic Circle some days do not have a sunrise or sunset.)

Our NST analysis shows a relationship between the diurnal solar cycle and freezing precipitation. During the day, freezing rain and freezing drizzle occur most frequently before sunrise, whereas the maximum frequency for ice pellets is a few hours after local noon (Fig. 3). The diurnal distribution for freezing rain is similar to the cycle found by Robbins and Cortinas (1996), although they used local time instead of NST. The frequency of freezing rain and freezing drizzle is highest during the coldest time of the day--the hour proceeding sunrise. Soon after sunrise the frequencies decrease sharply, with a slight increase and then a decrease shortly after local noon. Near sunset, both types of precipitation reach their lowest frequency of the day. The secondary maximum in frequency during the afternoon suggests that afternoon heating may contribute to an increase in precipitation at that time.

Unlike freezing rain and freezing drizzle, ice pellet frequencies ***increase*** gradually after sunrise and reach their maximum frequency within two hours after local noon, increasing 50% over the average frequency during nighttime hours. This distribution suggests that daytime heating plays an important role in the production of ice pellets. Past research has shown that the occurrence of ice pellets may be highly sensitive to the strength of the melting zone (e.g. Hanesiak and Stewart 1985). Thus, daytime heating may have some effect on the strength of the melting zone and/or the refreezing zone below. The simultaneous decrease in freezing rain may also be

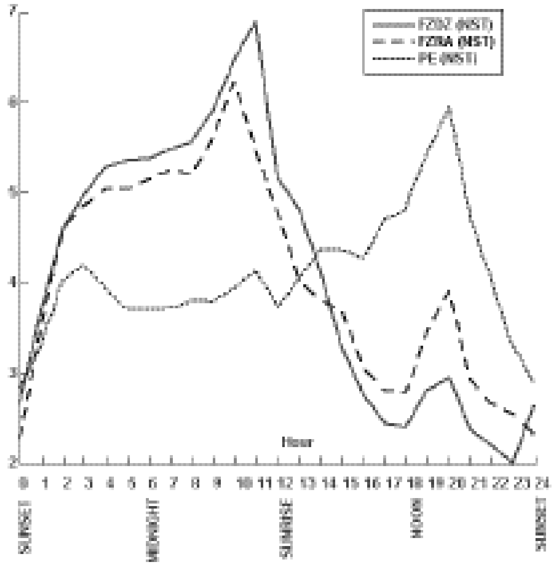

Fig. 3. Frequency (%) of different freezing precipitation types by normalized solar time, where FZRA = freezing rain, FZDZ = freezing drizzle, and PE = ice pellets.

related to this, but could simply be the result of a changeover to rain caused by increasing surface temperatures. Additional research is necessary to provide a more complete explanation for this frequency maximum after noon.

3.3 ***Duration***

We evaluated the duration of each precipitation type by counting the number of sequential hourly observations of each type. Given this definition, two

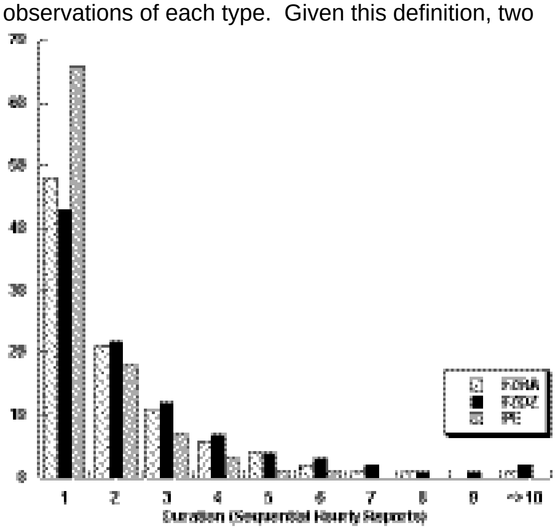

Fig. 4. Duration frequency (%) of different types of freezing precipitation, where FZRA = freezing rain, FZDZ = freezing drizzle, and PE = ice pellets.

reports of freezing rain with a one-hour break would be counted as two one-hour events. Although one could arbitrarily define an event many ways, Cortinas (2000) shows that for freezing rain, increasing the number of intervening hours did not significantly change the final results since freezing rain events typically do not have long intervening periods of no precipitation.

The duration of most freezing precipitation events is less than two hours, with ice pellets making up the largest percentage of these short-lived events. The decrease in the frequency of events with increasing event time is nonlinear and decreases to less than 1% for ice pellets and freezing rain, and 1% for freezing drizzle for an event duration of 9 hours. Although most freezing precipitation events are short-lived, it is important to note that 5% and 9% of freezing rain and freezing drizzle events respectively lasted longer than five hours. These long-lived events may product the most hazardous conditions for aircraft and ground operations. Most common, short-lived events, however, are the most difficult to forecast because the meteorology associated with them occurs on small spatial and temporal scales.

3.4 *Concurrent Weather Conditions*

We analyze other surface conditions associated with freezing precipitation in order to understand which conditions may provide useful information to forecasters anticipating freezing precipitation and icing conditions at the surface and aloft. These surface conditions also provide information about the predominant processes that control the evolution of the freezing precipitation. In this study we examined concurrent types of precipitation and the surface (10 m) air temperature.

Surface observations reveal that most freezing rain and freezing drizzle occur in the absence of other types of precipitation, whereas ice pellets are mixed most often with snow (Table 1). This analysis, however, does not indicate how often freezing precipitation changes into another precipitation type before ending. The high percentage of freezing rain and freezing drizzle observations without other

Table 1. Frequency (%) of concurrent precipitation observations. Columns indicate predominant type of precipitation and may not add up to 100% since more than one type of precipitation can be reported with the predominant type (FZRA=freezing rain, FZDZ=freezing drizzle, PE=ice pellets, RA=rain, SN=snow, T=thunder)

	FZRA	FZDZ	PE
FZRA	-	1%	18%
FZDZ	2%	-	3%
PE	18%	2%	-
RA	0%	1%	19%
SN	14%	24%	35%
T	1%	0%	1%
NONE	69%	74%	32%

precipitation types may indicate that the presence of large amounts of ice in cloud eventually inhibits freezing rain and drizzle through glaciation processes. Ice pellets, however, are usually mixed with other types of precipitation. The low percentage of freezing drizzle observations with ice pellets suggests that drizzle-ice collisions are efficient at converting drizzle to ice pellets. This may also be why some ice pellet events are short-lived (Fig. 4).

Because the surface temperature is an important factor in determining the precipitation type at the ground, we examined the surface temperature for all reports of freezing precipitation. Our analysis shows that freezing precipitation is associated most frequently with surface temperatures near 0˚C (Fig. 5), although freezing rain, freezing drizzle, and ice pellets have occurred at temperatures as low as -38˚C, -31˚C, and -41˚C respectively. The high frequency of freezing rain and freezing drizzle reports with a surface temperature near 0˚C supports the hypothesis that the lack of active ice nuclei near 0˚C inhibits the formation of ice particles in cloud, minimizing the liquid depleting growth of ice that would counteract the continued existence of freezing rain and/or drizzle.

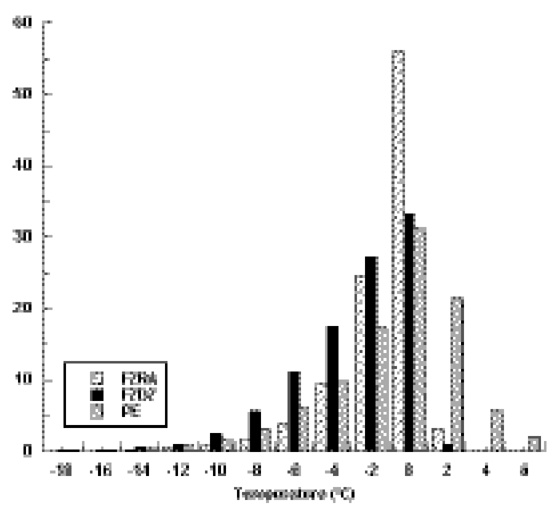

Fig. 5. Frequencies (%) of precipitation types associated with different surface temperatures (˚C).

4. CONCLUSIONS

In this study we investigated the climatological distribution of freezing precipitation and these are the key findings.

- This is large spatial variability in the annual frequency of freezing precipitation across North America. These precipitation types occur most frequently across the central and eastern portions of the US, and Canada, as well as the northern shores of Alaska and Canada.

- The spatial distribution of freezing precipitation suggests that topographical features, water source proximity, and location relative to climatological extratropical cyclone tracks may determine the climatology of freezing precipitation.
- Freezing precipitation occurs most often from December – March. This precipitation, however, occurs in northern Canada and Alaska throughout the year.
- Freezing precipitation appears to be linked with the diurnal solar cycle. Freezing rain and freezing drizzle occur most often just before sunrise, whereas ice pellets occur most often several hours after local noon. All types of freezing precipitation have their lowest frequency at sunset.
- Freezing precipitation is often short-lived; however, 5% and 9% of freezing rain and freezing drizzle events respectively lasted for more than five hours.
- Most freezing rain and freezing drizzle is not mixed with other precipitation types, whereas most reports of ice pellets also included other types of precipitation. Snow is the most frequent type of precipitation reported with freezing precipitation.
- Freezing precipitation occurs most frequently with a surface (10-m) temperature near 0˚C.

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